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1 **Human responses to multiple sources of directional information in virtual crowd**  
2 **evacuations**

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## 25 **Summary**

26 The evacuation of crowds from buildings or vehicles is one example that highlights the importance  
27 of understanding how individual-level interactions and decision-making combine and lead to the  
28 overall behaviour of crowds. In particular, to make evacuations safer, we need to understand how  
29 individuals make movement decisions in crowds. Here, we present an evacuation experiment with  
30 over five hundred participants testing individual behaviour in an interactive virtual environment.  
31 Participants had to choose between different exit routes under the influence of three different  
32 types of directional information: static information (signs), dynamic information (movement of  
33 simulated crowd), memorised information, as well as the combined effect of these different  
34 sources of directional information. In contrast to signs, crowd movement and memorised  
35 information did not have a significant effect on human exit route choice in isolation. However,  
36 when we combined the latter two treatments with additional directly conflicting sources of  
37 directional information, such as signs, they showed a clear effect by reducing the number of  
38 participants that followed the opposing directional information. This suggests that the signals  
39 participants observe more closely in isolation do not simply overrule alternative sources of  
40 directional information. Age and gender did not consistently explain differences in behaviour in our  
41 experiments.

42

43 **Keywords:** decision-making, crowd behaviour, emergency evacuations, virtual environment, route  
44 choice, directional information

## 45    **1. Introduction**

46    Imagine a crowd of people leaving a building with multiple exits. Some exits are labelled with signs,  
47    while some people in the crowd remember that they have been told to use certain exits. Which  
48    exit route do people choose? Do they follow the signs, or other people, or the information they  
49    may or may not remember? Depending on the decisions of individuals, the crowd could split  
50    evenly between different exits or everyone could try to use the same exit. This scenario is a perfect  
51    example of collective behaviour in which the decisions of individuals combine and lead to the  
52    observed crowd dynamics [1]. Such collective behaviour phenomena, emerging from interactions  
53    between individuals, occur across a wide range of species including social animals, insects or  
54    bacteria and include the synchronised movement of schools of fish or the relocation of nest sites in  
55    ants, for example [2].

56

57    The evacuation of human crowds from confined spaces is one example that highlights the practical  
58    importance of understanding collective behaviour. Crowds are composed of many individuals and  
59    each individual makes movement decisions based on their surroundings. These individual-level  
60    decisions give rise to the movement dynamics of crowds and to make buildings or vehicles safer,  
61    we thus need to understand the individual-level decisions in crowd evacuations [3]. Individuals  
62    within a crowd are likely to make movement decisions at different temporal and spatial scales [4].  
63    In particular, it has been suggested that we need to distinguish between microscopic ‘operational  
64    level’ decisions and higher level ‘tactical level’ decisions [5]. Operational level decisions typically  
65    relate to the short time-scale walking behaviour of pedestrians, such as the precise steps in a path  
66    an individual may take through a crowd to the nearest exit whilst avoiding collisions with other  
67    pedestrians or objects in the vicinity. Theoretical and empirical research on this type of behaviour  
68    suggests that humans seek to optimise their travel time or the directness of their path [6,7].

69 Tactical level decisions occur over longer timescales, and examples include the decision on which  
70 exit route from a building to use, or the timing of when to initiate the personal evacuation. In the  
71 context of evacuations, tactical level decisions about when to go and where to go can lead to high  
72 pedestrian densities and operational level behaviours can subsequently lead to potentially  
73 dangerous collective phenomena, such as the build-up of pressure at bottlenecks in evacuation  
74 routes [5]. Empirical and theoretical work has greatly helped to reduce the risks posed by  
75 dangerous collective phenomena emerging from behaviour at the operational level [3]. In this  
76 study, we investigate the tactical level movement decisions of humans in the context of crowd  
77 evacuations.

78

79 Different approaches have been developed and used to determine what individual-level  
80 behaviours may lead to observed collective phenomena, but there is currently no established  
81 solution for this particular problem. In one approach, different models for individual behaviour are  
82 fitted to empirical data. The model producing the best fit represents the most likely set of  
83 behaviours [8]. A drawback of this approach is that our knowledge is always limited by the  
84 available models for behaviour under consideration. A different approach treats individuals as  
85 particles and estimates the strength of the forces acting between these particles from the relative  
86 movement of individuals [9,10]. Manipulating the sensory abilities of individuals within groups  
87 (e.g. by blindfolding them), presents another approach to establish the sufficient and necessary  
88 basis for certain types of collective behaviour [11]. We employed an alternative approach by using  
89 a virtual environment to precisely control the signals and visual stimuli humans could obtain from  
90 their environment. By asking volunteers to complete an evacuation from a building in this  
91 interactive simulated environment, we investigated how humans respond to different sources of  
92 information when making movement decisions.

93

94 Interactive virtual environments are an established and proven tool to investigate dynamic human  
95 decision making in response to changing circumstances in general [12,13] and in evacuations in  
96 particular [14-18]. At one end of a spectrum of simulated environments are 'table-top' pen and  
97 paper scenarios developed to assess decision making of miners, fire-fighters or military personnel  
98 in emergencies that can subsequently be used for training purposes [19]. At the other end of the  
99 spectrum for simulated environments are fully immersive scenarios for pedestrians that promise to  
100 be useful in calibrating models for pedestrian movement and in exposing volunteers to fully  
101 controlled emergency situations [20]. We opted for an intermediate level of simulation  
102 sophistication. This ensured the simulated scenario was realistic enough to be easily understood by  
103 participants and that the controls for interactions with the environment were sufficiently simple to  
104 allow a wide spectrum of volunteers to participate. An additional advantage of performing  
105 experiments on human behaviour in crowd evacuations using a virtual environment is that we can  
106 expose many participants to different, potentially stressful, scenarios at low cost and without risk  
107 of injury or exhaustion. A disadvantage of conducting experiments in virtual environments, which  
108 we address further below, is the question to what extent findings from this type of research apply  
109 to real evacuations.

110

111 The scenario outlined in the introductory paragraph illustrates how individuals may base their  
112 movement decisions on different sources of information. We identified three ubiquitous sources of  
113 information or signals for the purpose of this study: emergency exit signs, the actions of other  
114 individuals within the evacuating crowd, and memorised instructions. The common aspect of these  
115 three sources of information is that they provide directional information that can steer evacuees in  
116 a particular direction during emergencies. Emergency exit signs provide static information that

117 does not change over time. The actions of other individuals within the evacuating crowd provide  
118 dynamic information that can change over time. Memorised information, such as verbal  
119 instructions given prior to the evacuation, may not be remembered correctly or could be forgotten.  
120 In the course of an evacuation, people are often confronted with possibly conflicting information  
121 from different sources [21]. Therefore, we suggest that it is particularly important to assess the  
122 effect of combinations of signals on individual decision-making in the context of evacuations.  
123 Previous research has used interactive virtual environments to assess the response of humans to  
124 different static environmental directional information [15,18,22]. In contrast, we investigate the  
125 impact of static, dynamic and memorised directional information and the interplay between these  
126 information sources on human movement decisions.

127

128 Although some research suggests that the layout of buildings could be more important in  
129 informing evacuees' movement decisions [23], emergency exit signs are a commonly used and  
130 widely accepted tool to label exit routes [24]. Empirical research has also investigated where to  
131 best position signs and how to design signs to ensure their visibility [15,22]. Interactive virtual  
132 environments have previously been used to investigate the effect of signs on human movement  
133 decisions [16,18]. The results suggest that on the one hand signage can reduce evacuation times  
134 but on the other hand that humans tend to preferentially interact with other conspicuous features  
135 of the virtual environment, such as doors or brightly lit and wider corridors, and that only repeated  
136 exposure to signs has the desired effect [16,18].

137

138 Crowd-following behaviour is often considered to be an important aspect of evacuations and it has  
139 been suggested that this could be beneficial in some circumstances by helping people to find exits,  
140 but conversely, could also lead to overcrowding at exits in other circumstances [25]. In addition,

141 proximity seeking behaviour towards familiar people is considered to be important [26]. However,  
142 in general the question of whether evacuees follow others remains unresolved and is likely to  
143 depend on the specific context [5].

144

145 Official guidelines recommend that passengers of planes or trains are invited to familiarise  
146 themselves with the location of emergency exits and to note the closest emergency exit to their  
147 seat [27]. Similar instructions may be given on entering buildings or people may notice and  
148 possibly memorise exit routes on a tour around a building. While previous work investigated the  
149 importance of being familiar with one of a choice of exit routes [17,28], to our knowledge the  
150 effect of memorised information on the movement decision of evacuees has not been investigated  
151 systematically.

152

153 In summary, we used an interactive virtual environment to investigate how the information from  
154 three different sources of directional information influence the movement decisions of humans in  
155 simulated evacuations. Importantly and in contrast to previous work, we not only investigate the  
156 effect of different signals in isolation, but also explicitly consider combinations of signals in which  
157 the directional information of one signal is either reinforced or contradicted by another signal.

158

159

## 160 **2. Methods**

161

### 162 ***2.1 Methods summary***

163 In this research we extend established methodology for studying human route choices in a virtual  
164 environment [17]. We recruited participants from paid volunteers taking part in a separate large-



165 scale experiment on pedestrian dynamics in Düsseldorf, Germany (19<sup>th</sup> – 22<sup>nd</sup> June 2013; project  
166 details: [www.basigo.de](http://www.basigo.de)). Each participant was only allowed to take part in the experiment once  
167 and was presented with a top-down view of a virtual environment populated by eighty simulated  
168 pedestrians, the movement of one of which could be controlled by participants via mouse clicks.  
169 Figure 1 shows this environment: the layout was symmetrical and consisted of a central room, an  
170 entrance area and two corridors connecting the central room to an additional corridor stretching  
171 over the width of the environment. The global environment was hidden from participants, and  
172 only the contents of the rooms they were occupying were visible to them (figure 1). We recorded  
173 the timing and the on-screen location of mouse clicks for each participant, as well as the associated  
174 movement within the virtual environment. At the start of the experiment, participants received  
175 instructions on how to steer their pedestrian (see supplementary information for full instructions).  
176 Our experiment consisted of three tasks participants had to accomplish within the virtual  
177 environment.

178

179 In the first task, participants were familiarised with the virtual environment and learned how to  
180 control their pedestrian by moving it from a starting position in the entrance area via a designated  
181 route marked with arrows to a fixed target in the central room (T1 in figure 1a). The symmetrical  
182 layout of our experiment allowed us to randomly choose one of the two possible routes into the  
183 central room for each participant to avoid inducing a directional bias. During this task the  
184 simulated pedestrians moved randomly in the central room and the two corridors (see  
185 supplementary methods for details). All participants successfully completed the first task. We did  
186 not use data from this task in our analysis.

187

188 At the start of the second task, participants were shown a message for six seconds instructing them

189 to leave the (central) room in case there was an emergency. In the remainder of the second task,  
190 participants were presented with nine maths questions and were invited to answer as many as  
191 possible within thirty seconds. They were subsequently shown the results of their performance in  
192 this test for fifteen seconds. This task was designed to distract participants from the instruction  
193 message at the start of the task. The content of the message was varied in one of the experimental  
194 treatments (see below).

195

196 The third task started with a five second countdown. Over the last four seconds of this countdown  
197 participants were shown a message instructing them to leave the room because of an emergency.  
198 The entrance by which participants had entered the central room in the first task was blocked and  
199 participants were thus faced with a choice of two exits from the room: one at the top and one at  
200 the bottom (figure 1). The third task and the experiment ended when participants reached a new  
201 target that was outside the central room and equidistant from both remaining exits (T2 in figure  
202 1a). During this task, the simulated pedestrians performed a simulated evacuation, exiting the  
203 room through the same exits that were open to the participants. To ensure that participants  
204 quickly grasped how to control their pedestrian, they were allowed to ask the experimenter  
205 questions throughout the experiment. Only answers on how to steer their pedestrian were given.  
206

## 207 **2.2 Treatments**

208 Each participant was exposed to one treatment out of ten possible treatments. To ensure an even  
209 split of participants across treatments, we allocated a unique number to each participant which  
210 was incremented by one between consecutive participants and allocated treatments according to  
211 modulo 10 of this number. Participants were not allowed to watch others before they took part in  
212 the experiment and participants who had already taken part in the experiment were not allowed to

213 talk to others before they took part. In addition to the control treatment, we implemented three  
214 primary treatments. We obtained six additional treatments by pair-wise combinations of the three  
215 primary treatments. The treatments were designed to provide participants with directional  
216 information about which exit route to take and are described below.

217

218 In the control treatment, the simulated pedestrians split evenly between the two exit routes from  
219 the central room during their simulated evacuation (see figure 1a). This treatment was designed to  
220 establish the base-line behaviour of participants in a perfectly symmetrical setup.

221

222 In the 'memory' treatment (M), participants were shown a different message at the start of the  
223 second task. Whilst in the other treatments the message only instructed participants to leave the  
224 room in case of emergency, in the M treatment, the message instructed participants to leave the  
225 room through a specific exit. Both exits and the entrance were labelled with unique symbols that  
226 were shown six times for half a second in half-second intervals (see figure 1b). The message  
227 indicated the unique symbol of the exit participants should use when exiting the room. The M  
228 treatment was designed to test participants' ability or willingness to follow instructions on exit  
229 routes from memory. In real life people might be distracted during or after receiving information  
230 on exit routes and we included the maths test in the second task to distract participants from the  
231 information received in the M treatment.

232

233 The 'crowd' treatment (C) presented participants with a simulated evacuation in which all  
234 simulated pedestrians exited through one exit (see figure 1c). This treatment tested the response  
235 of participants to the dynamic directional information provided by the movement of simulated  
236 agents and it also tested participants' response to exit blockages induced by the simulated crowd.

237

238 In the 'sign' treatment (S), the simulated evacuating crowd split evenly between the two exits, but  
239 close to one of the exits was a green 'EXIT' sign with an arrow pointing upwards or downwards,  
240 depending on which direction people had to move to use the nearby exit (see figure 1d). The S  
241 treatment was designed to test participants' response to static directional information provided by  
242 signs.

243

244 The remaining six treatments were pair-wise combinations of the primary treatments M, C and S.  
245 In three of these treatments, the two primary treatments reinforced the directional information  
246 they provided to the participants. For example, in the reinforcing combination of the crowd  
247 treatment C and the sign treatment S (denoted interchangeably by C+S or S+C), the simulated  
248 crowd exited through the same exit that was also marked with an exit sign. Likewise, in treatment  
249 M+S (or S+M), the exit indicated to participants at the start of the second task was also labelled  
250 with an exit sign. The remaining treatment that reinforced directional information was M+C (or  
251 C+M).

252

253 To study the case when different sources of information provide conflicting directions, we  
254 combined the primary treatments in such a way that they suggested opposite exit routes. For  
255 example, in the conflicting combination of treatment C and treatment S (denoted interchangeably  
256 by C-S or S-C), the simulated crowd all exited through one exit while the opposite exit was marked  
257 with an exit sign. The other conflicting combinations of primary treatments led to treatment M-S  
258 (or S-M) and treatment M-C (or C-M).

259

260 All procedures of our experiment were approved by the Ethics Committee of the University of

261 Essex.

262

### 263 **2.3 Simulated individual behaviour**

264 We used previously established methodology [17] based on well accepted theoretical work [25,29]  
265 to simulate the movement of pedestrians in continuous space. We modelled interactions between  
266 pedestrians as social forces. Individuals' reactions to the built environment (e.g. walls) and  
267 movement preferences (e.g. towards a target) were encoded in a discrete floor field. At the start of  
268 the experiment, the simulated pedestrians were distributed randomly over the central room and  
269 the two adjoining top and bottom corridors (see figure 1a). Pedestrian-pedestrian and pedestrian-  
270 wall overlaps were avoided throughout the experiment and simulated pedestrians were removed  
271 from the simulation and graphic display when they reached the final target of the evacuation in the  
272 third task. During the first task, a small number of pedestrians (<4%) occasionally entered the  
273 entrance area, where they got stuck when the entrance was blocked during the third task (this had  
274 no effect on experimental outcomes). The movement dynamics in the virtual environment were  
275 not updated during the second task and whenever messages were displayed to the human players.  
276 We ran the simulation with fixed parameter values to ensure that simulated pedestrians moved at  
277 a reasonable speed and participants had sufficient time to react to the dynamics. The full details of  
278 the simulation model can be found in the supplementary information.

279

### 280 **2.4 Data collection and statistical analysis**

281 Only participants aged 18 or older were permitted to participate in the research. We recruited a  
282 total of 570 participants, 29 of whom had to be excluded from the study because they accidentally  
283 terminated the computer program before the complete data could be written to files. Of the  
284 remaining 541 participants, 450 (83%) reported their age. The median age across participants was

285 23 years (mean: 24.66 years), the minimum and maximum ages were 18 and 66 years, respectively.  
286 A total of 505 (93%) participants reported their gender. Slightly more men than women  
287 participated (287 and 218, respectively). We did not record data on nationality or ethnicity. We  
288 used the movement and mouse clicks of participants in the virtual environment during the third  
289 task to compute the following summary statistics.

290

291 *‘Following information’*: Each of the primary treatments M, C and S provided participants with a  
292 signal in the form of directional information. This binary summary statistic took value 1, if  
293 participants used the same exit as indicated by this signal and value 0 otherwise. For example, if a  
294 participant used the same exit as the crowd in treatment C, this participant was assigned value 1  
295 for this summary statistic. We then used the fraction of individuals who used the exit indicated by  
296 the crowd,  $P(\text{same as signal})$ , to summarise participant behaviour. When treatments were  
297 combined, we split  $P(\text{same as signal})$  up into  $P(\text{same as memory})$ ,  $P(\text{same as crowd})$  and  $P(\text{same as}$   
298  $\text{sign})$ . In treatments where different signals reinforced directional information, the ‘follow  
299 information’ summary statistic was identical for both of the separate signals. For example, in  
300 treatment M+S,  $P(\text{same as memory}) = P(\text{same as sign})$ . In treatments where different signals  
301 provided competing directional information, the ‘follow information’ summary statistics were  
302 different for the two signals but summed to 1 as there was a binary choice of exits. For example, in  
303 treatment S-C,  $P(\text{same as crowd}) + P(\text{same as sign}) = 1$ .

304

305 *‘Click number’*: We recorded the number of mouse clicks participants performed in the third task.  
306 This is a measure for how often individuals adjusted their movement and could be related to  
307 growing impatience, attempts to avoid the crowd or obstacles, or simply individual preferences for  
308 steering the agent.

309

310   *'Reaction time'*: We defined the time it took participants to show a reaction at the start of the  
311   evacuations as the number of simulation time-steps between the end of the countdown before the  
312   simulated evacuations and the first mouse click. This time could indicate whether participants  
313   contemplated different possibilities before making a decision or it could simply measure how fast  
314   participants can respond at the end of the countdown.

315

316   *'Adaptation'*: With this binary summary statistic, we measured whether or not participants  
317   changed their mind when leaving the central room. We defined these changes of mind as the case  
318   when participants moved at least one fifth of the height of the central room in the vertical  
319   direction towards one exit before exiting through the opposite exit. This summary statistic could  
320   indicate the ability or willingness of participants to adapt their initial decision in response to the  
321   developing simulated evacuation. As for *'Following information'* we report the fraction of  
322   individuals who changed their mind,  $P(\text{change mind})$ .

323

324   We conducted our statistical analysis in the R programming environment, version 2.15.2 [30], and  
325   applied two types of statistical tests to the data. First, we used binomial tests to determine  
326   separately for each treatment whether the probabilities  $P(\text{follow signal})$  and  $P(\text{change mind})$  were  
327   different to what we might expect by chance. We also obtained 95% confidence intervals for these  
328   probabilities using the approach included in the binomial test implementation in R. Second, we  
329   compared summary statistics between different treatments using generalized linear models  
330   (GLMs), as described below.

331

332   We used GLMs to test for the influence of treatment, age, gender and performance in the maths

test on summary statistics. We included participants' performance in the maths test in our statistical analysis to investigate whether the range of abilities needed to do well in the maths test had an effect on decision-making. In addition to arithmetic abilities, the maths test provided a measure for participants' computer literacy (text fields had to be filled in quickly) and their ability to perform under time pressure. For the two Boolean summary statistics (follow information, adaptation), models had binomial error structure with logit link functions. The other two summary statistics were fit to standard linear models with Gaussian error structure. We performed a log transformation to reaction time data prior to model fitting to meet normality assumptions. All models included an intercept, the response variable was the summary statistic and the explanatory variables were treatment (categorical), age, gender (categorical) and performance in the maths test (number of correctly answered questions). Using these statistical models, we conducted pairwise comparisons of treatments for the primary treatments. We also compared combinations of treatments against a baseline of each primary treatment in turn. For these comparisons, we used one of the above-mentioned statistical models to assess the effect of each combined treatment on a summary statistic, taking age, gender and performance in the maths test into account. We report the full output of the statistical models in the supplementary information.

As a result of the number of treatments and summary statistics we consider, we conduct many comparisons in our statistical analysis. To avoid Type I errors (false positives), we would have to adjust our significance thresholds for multiple comparisons. However, doing so would inflate the false negative rate. We suggest that in the context of crowd evacuations, we should be careful not to rule out possible factors affecting human decision making falsely (false negatives) as ignoring such factors may have disastrous consequences. Initially considering factors that are shown to have no effect by further experiments (false positives) may incur a cost in terms of research effort, but is



less likely to lead to omissions in contingency plans for emergencies and in future research on the topic. Therefore, we do not adjust for multiple comparisons and set the significance threshold to  $P < 0.05$  throughout. Since we report all p-values, the inclined reader can perform an adjustment for multiple comparisons post-hoc.

### 3. Results

We first present the effect of the primary treatments on the exit choices of human participants in our virtual environment. Subsequently, we show the effect of combining treatments on human route choice using each primary treatment in turn as a baseline for behaviour. As described in the methods, the symmetrical setup of the experiment enabled us to randomly choose the directional information provided by the treatments between the upper and lower route. While this should be sufficient to create a balanced experiment without bias, we nevertheless tested whether participants chose the upper or lower route more often than we would expect by chance in the absence of directional information (control treatment). We found this was not the case (binomial test:  $P = 0.68$ ). We also found no consistent effect of the additional individual-level characteristics we recorded (age, gender, performance in the maths test) on subject behaviour. The specific results and a discussion relating our findings on the effect of individual characteristics to previous research can be found in the supplementary information.

#### 3.1 Effect of primary treatments (Memory, Crowd, Sign)

Figure 2a shows significant differences in the fraction of participants following the directional information provided by the different primary treatments. For the memory treatment (M) and the crowd treatment (C), the proportion of participants following the directional information provided

381 was not significantly different to that expected by chance (binomial test:  $P=0.15$  and  $P=0.13$ ,  
382 respectively). Nevertheless, the likelihood of participants to follow the directional information in  
383 the M treatment was so low, that we found a statistically significant difference between this  
384 treatment and treatment C (SI table 2). The static directional information provided in the sign  
385 treatment (S) was followed by over eighty percent of participants, more than expected by chance  
386 (binomial test:  $P=5.81 \times 10^{-9}$ ), and this response was significantly higher than the response in both  
387 treatments M and C (SI tables 1,3).

388

389 Neither the reaction time (figure 2b), nor the total number of clicks (figure 2c) of participants  
390 showed significant differences between treatments (SI tables 4-15). The difference in reaction  
391 times between treatments C and S seems to be considerable under visual inspection (figure 2b),  
392 but these data had to be log-transformed before statistical analysis and the absolute differences  
393 between treatments were thus reduced.

394

395 The probability for participants to change their original decision was low for all treatments and  
396 significantly different from random (binomial test, treatments: Control, M, C, S;  $P=1.65 \times 10^{-13}$ ,  
397  $P=4.09 \times 10^{-16}$ ,  $P=2.92 \times 10^{-12}$ ,  $P=7.08 \times 10^{-10}$ , respectively; figure 2d). Although this probability seemed  
398 to increase from treatment M to C to S, as with the probability to follow the directional  
399 information provided by the treatments (figure 2a), the difference between treatments was not  
400 statistically significant (SI tables 16-21). Across the three treatments M, C and S, only nine people  
401 changed their initial decision. Six of these participants initially moved in the opposite direction as  
402 indicated by the treatment and then changed their mind. This proportion is not significantly  
403 different than expected by chance (binomial test:  $P=0.51$ ). As an aside, note that across all  
404 combined treatments that provided non-conflicting directional information (M+S, M+C, S+C),

eleven out of twelve participants who changed their mind adjusted their initial decision to move in the direction suggested by the treatment. This proportion was higher than expected by chance (binomial test:  $P=0.0064$ ).

408

Considered on their own, these results suggest that the only source of directional information in our experiments that had a significant effect on participants' decision-making and behaviour was the static directional information provided by signs. Furthermore, these results also suggest that there is no significant difference in the time taken by participants to make their initial decision about where to move, and that participants tend to stick with their original decision about which exit to leave from.

415

In the following results, we no longer present the reaction time, number of mouse clicks participants performed and the probability of participants to adjust their initial decision as the different treatments had no significant effect on these summary statistics (with one exception, see SI figure 1). Results on these summary statistics can be found in the supplementary information (SI figure 1).

421

### **3.2 Effect of crowds and signs in the presence of memorised information (M+S, M+C, M-S, M-C)**

We compared reinforcing and conflicting combinations of primary treatments against the baseline of the memory treatment, M (figure 3a). When the directional information provided by memory was reinforced by the directional information of the sign (M+S) or crowd (M+C), the proportion of participants following this information increased significantly when compared to the baseline M treatment (SI table 22), and was significantly higher than expected by chance (binomial test: treatment M+S,  $P=5.55 \times 10^{-6}$ ; treatment M+C,  $P=8.02 \times 10^{-4}$ ; figure 3a). The effect of conflicting

directional information on the route choice of participants in treatments M-S and M-C compared to treatment M was not statistically significant (SI table 22). However, the fraction of participants following the directional information provided by memory in these treatments was reduced and significantly lower than expected by chance, which was not the case in treatment M (binomial test: treatment M-S,  $P=0.0012$ ; treatment M-C,  $P=0.013$ ; figure 3a).

These results confirm that memory (treatment M) had a weak effect on subject behaviour. In the original treatment M, the proportion of individuals following the directional information provided by memory was no different than expected by chance. However, in treatments where the directional information from memory was reinforced by the movement of the crowd or the presence of a sign, significantly more participants than expected by chance followed the directional information provided by memory. In treatments with conflicting information, significantly fewer participants than expected by chance followed the directional information provided by memory.

### **3. 3 Effect of signs and memory in the presence of crowds (C+S, C+M, C-S, C-M)**

In figure 3b we show comparisons of reinforcing and conflicting combinations of primary treatments against the baseline of the crowd treatment, C. When the directional information provided by the crowd was reinforced by a sign (treatment C+S), the proportion of participants following this information increased significantly (SI table 26). Combining the directional information of crowd and memory (C+M) also led to a higher proportion of participants following the information, but the increase compared to treatment C was not statistically significant (SI table 26). However for both treatments C+S and C+M, the proportion of participants following the directional information was significantly higher than expected by chance, which was not the case for treatment C alone (binomial test: treatment C+S,  $P=2.14 \times 10^{-10}$ ; treatment C+M,  $P=8.02 \times 10^{-4}$ ).

453 When the directional information of the crowd conflicted with the information provided by a sign  
454 (C-S), the proportion of participants following the direction of the crowd was reduced significantly  
455 (SI table 26). This was not the case when crowd and memory suggested opposite directions (C-M;  
456 SI table 26). The proportion of participants following the crowd actually increased slightly in  
457 treatment C-M compared to C and was now significantly different than expected by chance  
458 (binomial test:  $P=0.013$ ), while in treatment C-S it was not different than expected by chance  
459 (binomial test:  $P=0.081$ ). The latter p-value is only narrowly non-significant and further studies,  
460 possibly with more participants, may show a significant difference. These findings further  
461 corroborate the view that treatment S had a strong and treatment M a weak effect on participant  
462 decision-making and behaviour.

#### 463 464 **3.4 Effect of crowds and memory in the presence of signs (S+C, S+M, S-C, S-M)**

465 The sign treatment, S, appeared to have the strongest effect on participants' movement behaviour  
466 and decision-making when only a single source of directional information was given (figure 2). We  
467 now consider treatment S as a baseline and investigate the effect of reinforcing or contradicting  
468 the directional information provided by the sign with the directional information provided by the  
469 memory and the crowd (figure 3c). Reinforcing the directional information had no statistically  
470 significant effect on the proportion of participants following the direction indicated by the signs, as  
471 this proportion was already at a high level for treatment S alone (treatments S+C and S+M, SI table  
472 30). However, when the primary treatments were combined to provide conflicting information, the  
473 proportion of participants following the direction of the signs was significantly reduced compared  
474 to treatment S (treatments S-C and S-M, SI table 30). In treatment S-C this resulted in a proportion  
475 of individuals following the direction of the sign not significantly different from random (cf  
476 treatment C-S in section 3.3). So despite the fact that treatment C appeared not to have a

477 significant effect when it was the only source of directional information (figure 2a), the conflict  
478 between the directional information provided by the sign and the crowd was strong enough to  
479 significantly alter participants' tendency to follow the direction of the sign observed in treatment S  
480 alone (figure 2a). While the proportion of individuals following the direction of the sign was still  
481 higher than expected by chance in treatment S-M (binomial test,  $P=0.0012$ ), the fact that the  
482 difference between this treatment and treatment S was significant showed that memorised  
483 directional information had an effect when pointing in the opposite direction of signs. This finding  
484 was contrary to our previous results suggesting treatment M had a negligible effect when  
485 considered on its own.

486

487

#### 488 **4. Discussion**

489 We have conducted an extensive experiment with over five hundred participants and ten  
490 experimental treatments to test the responses of humans in simulated evacuations to different  
491 sources of directional information: static signs, dynamic crowd movements, and memorised  
492 instructions.

493

494 In agreement with previous work, we found that signs had a strong effect on human behaviour in  
495 simulated evacuations [16]. Previous work has suggested that the design, position and size of signs  
496 are important factors in determining peoples' response to them [15,22]. The strength of  
497 participants' response to the sign treatment in our experiment is therefore likely to be in part  
498 attributable to the comparatively large size and prominent position of the exit signs in our virtual  
499 environment. We found that people did not have a strong tendency to follow the simulated crowd.  
500 This agrees with the findings from an earlier study where we put participants under pressure to

501 complete a task faster [17]. Evidence from survivors suggests that affiliation and proximity to  
502 familiar people and between socially connected people occurs during crowd evacuations [26].  
503 Influential theoretical work has suggested for illustration purposes that during crowd evacuations  
504 and under stress, individuals may develop a tendency to follow others, a phenomenon called the  
505 'herding effect' [25]. It can be debated to what extent participants in our experiment interacted  
506 with simulated agents as they would with real people. Nevertheless, based on our results, we  
507 recommend further research on this subject and propose that crowd behaviour in evacuations is  
508 perhaps more nuanced than simple 'herd-like' following behaviour. Our experiment suggests that  
509 the movement of other pedestrians is merely one of many potentially influential sources of  
510 directional information individuals use to make movement decisions (see also discussion on  
511 combinations of information sources below). It could be argued that the time the message in the  
512 memory treatment, M, was displayed for (six seconds) was too short for participants to memorise  
513 the instructions and that the treatment would have a stronger effect if this time interval was  
514 increased. While the effect of the specific design of our treatments is important, we did not  
515 conduct experiments on this as we were primarily interested in studying the effect of combining  
516 different sources of directional information.

517

518 The combination of primary treatments provided intriguing results. In particular, the fact that the  
519 memory and crowd treatments did not affect human decisions in isolation, but had a significant  
520 effect when combined in a conflicting way with the sign treatment (compared to the baseline of  
521 the sign treatment) was interesting. This has a number of implications. First, contrary to the initial  
522 impression from the results, the memory treatment did have a significant effect (although not in  
523 isolation). Second, the treatment in which the sign and crowd provided conflicting information  
524 significantly reduced the proportion of people following the direction of the sign suggesting that a

525 considerable number of people followed the crowd. This is interesting as participants following the  
526 crowd risked getting stuck in the evacuating crowd even though the sign indicated an alternative  
527 that avoided this possibility. Third, these findings suggest that when treatments are combined, it is  
528 not the case that the treatment that participants observe more closely in isolation simply overrules  
529 the directional information suggested by alternative sources of information.

530

531 Controlled experiments on crowd evacuations from confined spaces all share one limitation: it is  
532 not ethical to recreate the real stress and potential dangers of evacuations. Thus, different  
533 approaches to investigate crowd evacuations are justified and valuable insights have been gained  
534 from interviews with survivors of crowd evacuations [26,28], evacuation drills with volunteers [31]  
535 and computer simulation models [7,25,29], for example. We have opted to use interactive virtual  
536 environments to study human behaviour in simulated evacuations. While the question of the  
537 extent to which our findings extend to real life human behaviour remains, we suggest that our  
538 study demonstrates virtual environments are a powerful tool for high throughput behavioural  
539 analysis. This type of experiment, possibly implemented online, could be used to select topics for  
540 further study in more life-like experiments from a large set of initial hypotheses.

541

542 One feature of our simulated evacuations that particularly distinguishes them from real life is that  
543 participants had a top-down view of the environment. We have previously argued that the tactical  
544 level decisions we investigate are likely to be based on features of the crowd dynamics that  
545 humans would be able to detect without having a top-down view, such as the length of queues at  
546 exits or the crowd's movement towards exits [17]. In addition, this way of representing the  
547 environment facilitates simple steering controls for interacting with the environment. Simple  
548 controls avoid the potential problem of more realistic, three-dimensional representations of



549 environments requiring more complicated controls that can lead to differences in performance  
550 between more and less experienced computer users (as reported in e.g. [32]). We additionally  
551 mitigated the problem of different levels in computer literacy between participants by focusing our  
552 study on route choices, as opposed to other performance measures, such as evacuation times, as  
553 studied in [16].

554

555 Fully explaining our findings on combined treatments is difficult with the data from our  
556 experiments. We only controlled the information participants had access to, but we did not collect  
557 self-report measures, such as data on the extent to which individuals identified with the pedestrian  
558 they controlled, to what extent they felt part of the simulated crowd and to what extent they  
559 trusted the different sources of directional information. Such measures could help to build up an  
560 understanding of the process of how participants made decisions based on the information  
561 available. An interesting avenue to explore could be the proposition that people have different  
562 propensities to react to different sources of information, in a similar way that different people  
563 prefer to learn from different sources of information (e.g. by classroom lessons, by reading, by  
564 working with peers, [33]). While the explanation of our findings remains for future research, we  
565 can conclude that it is important to provide evacuees with consistent directional information  
566 throughout the course of an evacuation. We acknowledge this can be difficult due to the specific  
567 circumstances of an evacuation [21]. However, our research shows that even memorised  
568 information that may not affect evacuees' behaviour in isolation may become an important factor  
569 in human decision making when combined with other sources of information.

570

571

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573

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578 collecting the data.

579

580

## 581 **6. Data accessibility**

582 The data presented in this manuscript is published as Electronic Supplementary Material alongside  
583 this article.

584

585   **7. References**

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689 **Figure Legends:**

690

691 **Figure 1:** Layout of simulated environment and different experimental treatments. (a) layout of the  
692 simulated environment. In the first task, participants started at the initial position 'St', followed  
693 arrows to the entrance 'En' into the central room 'CR' and to the first target 'T1'. The second task is  
694 outlined in the Methods and did not involve any simulated pedestrian movement. In the third task,  
695 participants started at 'T1' and subsequently left 'CR' through either exit into corridors 'C1' or 'C2'  
696 and moved to the final target 'T2'. The entrance 'En' was blocked in this task. The pedestrian  
697 steered by participants is represented by a black filled circle, located at 'T1', and simulated  
698 pedestrians are represented by white filled circles with a line indicating their movement direction.  
699 We show the control treatment in which the simulated crowd splits evenly between the two exits  
700 during the third task. For illustration purposes the whole environment is visible, but participants  
701 had a limited view as shown in the other panels. (b) Memory treatment M (the message displayed  
702 translates to: "Well done! During an emergency, leave the room through the exit marked with the  
703 following symbol: @"). (c) Crowd treatment C (the entire crowd exits through one exit). (d) Sign  
704 treatment S (the crowd splits evenly between the two exits and a sign labelled 'EXIT' indicates  
705 which exit to use),



**Figure 2:** Human responses to directional information in simulated evacuations. We extracted four  
summary statistics from participants' movement in the simulated environment and show the  
primary treatments and the control treatment. Under the control treatment the simulated crowd  
did not provide any directional information as it split evenly between the two exits. The primary  
treatments provided directional information: under treatment M, a message participants could  
memorise indicated the exit to use, in treatment C, the simulated crowd only used one exit and  
under treatment S, one exit was indicated by an 'EXIT' sign. (a) The proportion of participants using  
the same exit as indicated by the treatment (does not apply to the control treatment, as no  
direction is indicated). Numbers inside the bars indicate the number of participants per treatment  
and the symbols underneath indicate whether the observed proportion is significantly different  
from random ('\*') or not ('n.s.'). (b) The average number of simulation steps taken to react at the start of the evacuation, (c) the average  
number of clicks performed during the evacuation and (d) the proportion of participants who  
changed their original decision about which exit to use. The reaction time in (c) is given in update  
steps of the simulation (corresponding to 0.05 s of simulated time, see supplementary material).  
Statistically significant effects of treatments on summary statistics in pair wise comparisons of  
treatments are indicated by horizontal bars and asterisks ('\*') above the measured quantities (from  
GLMs, see Methods and supplementary information). Error bars show standard errors in (b) and  
(c), and 95% confidence intervals for the observed probabilities in (a) and (d). Further details on  
the statistical analysis can be found in the Methods section.

726 **Figure 3:** Human responses to reinforced or conflicting directional information in simulated  
727 evacuations. We used each of the primary treatments M, C and S in turn as a baseline (baseline M:  
728 a; baseline C: b; baseline S: c). We show the proportion of participants that followed the baseline  
729 signal. Additional summary statistics can be found in the supplementary information. Statistically  
730 significant effects of combined treatments compared to the baseline primary treatment are  
731 indicated by horizontal bars and asterisks ('\*') above the measured quantities (from GLMs, see  
732 Methods and supplementary information). The summary statistics and figure labelling is otherwise  
733 identical to figure 2. Recall that treatments M-C in (a) and C-M in (b) denote the same treatment.  
734 For this treatment we have  $P(\text{same as memory}) + P(\text{same as crowd}) = 1$ , as the directional  
735 information of M and C in this treatment points in opposite directions. Likewise, the values for  
736 M+C (or C+M) are identical in (a) and (b) as in this treatment the directional information for M and  
737 C coincide.





